LRFD

Section 3.81

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CLICK HERE TO Index

3.81.1 General

1.1 Design Criteria

Drilled shafts can be an economical alternative to spread or pile footings. They have the capability to handle large loads and can be constructed in a wide variety of soils.

A thorough site investigation must be completed to ensure proper soil characteristics.

Rock Properties
For drilled shafts socketed into rock, the uniaxial compressive strength, q_u, needs to be determined. Other factors that need to be determined are the Rock Quality Designation (RQD), and possibly joint or crack characteristics such as the spacing and thickness of the discontinuities, and the rock type.

Cohesive Soil Properties
The mean undrained shear strength, S_u, is required to determine resistance.

Cohesionless Soil Properties
The average standard penetration test blow count, N_{60}, will be required to determine resistance in sands or silts.

Materials
Concrete used for drilled shaft construction shall be Class B-2, f'_c = 4.0 ksi.

Dimensions
LRFD 10.8.5.1 Drilled shafts shall be sized in six inch increments. The minimum diameter shall be 18 in. unless the shaft is manually inspected. For manually inspected shafts the minimum diameter shall be 30 in.

The length to diameter ratio of the drilled shaft should be in the following range:
$3 \leq L/D \leq 30$

Initial size and length of drilled shafts shall be estimated by the vertical loads applied to the foundation. The size may have to be adjusted if large lateral loads are present. For shafts rock socketed, length of sockets are usually kept at the minimum length required, to reduce cost.

LRFD 10.8.1.3 When rock sockets are used, the diameter of the socket shall be 6 in. less than the inside diameter of casing when casing is used through the overburden soils. For shafts not requiring casing, the rock socket diameter may be the same size as the shaft diameter.

Where there is a column to drilled shaft connection, the drilled shaft diameter shall be a minimum of 6 in. larger than the diameter of column.

LRFD 10.8.1.3

When the base is cleaned and inspected, the entire base can be considered effective in transferring load.

Limit States

The Strength limit states and applicable Extreme Event limit states shall be investigated when calculating the soil and structural capacity of the drilled shaft.

Service I Limit State shall be used to investigate allowable lateral deflection and settlement.

1.2 Analysis

To analyze laterally loaded drilled shafts, the point of fixity of the drilled shaft must be obtained. This location may be obtained by using a computer program. This is an iterative process that requires you to first assume a point of fixity so that the bent stiffness may be calculated.

The stiffness of the bent may be found by modeling the bent in a structural analysis program, applying a load to the middle of the beam cap and measuring the amount of deflection that load causes. The moment of inertia of the bent is then found by:

$$I = \frac{\left(P/\delta\right)L^3}{3E}$$

Where:

I = moment of inertia of the bent
P = load applied to middle of beam cap
δ = deflection caused by load, P
L = length from point of fixity of drilled shaft to middle of beam cap
E = modulus of elasticity of concrete

When the moment of inertia of the bent is calculated, the longitudinal forces applied to the bent can be calculated. Once loads are obtained, they can be input into computer software to get a point of fixity.

If the point of fixity is different than what was assumed to obtain the original bent stiffness, then the bent stiffness will have to be calculated again with a new assumed point of fixity. This process shall be continued until the point of fixity location converges.
Tip: Usually shafts socketed into rock are fixed at approximately the rock elevation.

1.3 Design Considerations

Scour
The possibility of scour and its effect on the bearing and lateral capacity shall be investigated.

Ground Water
Effects of variable ground water levels and buoyancy shall be taken into account with the capacity.

LRFD 10.8.1.5
LRFD 10.7.1.4

Downdrag
Downdrag shall be considered when bearing resistance and settlement are investigated. For drilled shafts socketed into rock and overlayed with soil that has the potential to settle, downdrag shall be considered as an applied load. Downward movements of 0.1 to 0.5 in. are enough to mobilize full downdrag. The top 5 ft. and a bottom length equal to the shaft diameter shall not be included in calculating downdrag. Allowance shall be given for an increase in the undrained shear strength as consolidation of the soil occurs.

LRFD 10.8.7.3.2

Uplift
Shafts in cohesive soils, not socketed into rock shall be investigated for the affects of uplift.

LRFD 10.7.2

Movement
Settlements and lateral movements shall be designed at the Service I Limit State.

LRFD 10.7.2.2

Design lateral movements should not exceed 1.5 in. at the top of the shaft.

For shafts socketed into rock, settlement shall only be investigated to determine if the resistance of the shaft is from side or end bearing.

For shafts not socketed into rock, settlement shall be investigated. For cohesionless soils, all loads specified in the Service I Load combination shall be used. For cohesive soils, transient (live load) loads may be omitted. See Structural Project Manager for allowable settlement.

LRFD 10.7.2.3.2

Settlement for cohesive soils can be estimated with the same procedure for calculating settlement for shallow foundations.

LRFD 10.7.2.3.3

Settlement for cohesionless soils can be estimated by the following equations.

For SPT:

$$\rho = \frac{2qI\sqrt{X}}{N_{corr}}$$

For CPT:

$$\rho = \frac{qXI}{2q_c}$$

Where:

I = 1 - 0.125D'/X ≥ 0.5

$$N_{corr} = \left[0.77\log_{10}\left(\frac{20}{\sigma_v'}\right)\right]N$$

q = applied load divided by equivalent area of footing
X = width or smallest dimension of pile group
D' = effective depth = $2D_b/3$
D_b = depth of embedment of piles in layer that provides support
N = measured SPT blow count within the seat of settlement
σ'_v = effective vertical stress
q_c = average static cone resistance over a depth of X below the equivalent footing

LRFD 10.8.3.9.2, 10.8.3.9.3

Group Effects

Drilled shafts shall not have a center-to-center spacing closer than 2.5D. Shafts in cohesive and cohesionless soils, having center-to-center spacing in between 2.5D and 6D, shall be multiplied by an axial load reduction factor, η.

For shafts spaced at 2.5D:
η = 0.65
For shafts spaced at 6.0D:
η = 1.0

An intermediate spacing shall be linearly interpolated from the above η values.

LRFD 10.7.3.10.2

For cohesive soils, the capacity shall be determined from the lesser of the group capacity of drilled shafts or from the capacity of an equivalent pier which includes the block of soil within the area bounded by the drilled shafts.

3.81.2 Geotechnical Resistance

Geotechnical Resistance
If the drilled shaft resistance is determined by load test, then the ϕ factor applied shall be as follows, regardless of the soil conditions:
$\phi = 0.7$

2.1 Cohesive Soils

LRFD 10.8.3.3

Resistance in Cohesive Soils
Ignore top five feet of shaft and bottom of shaft length equal to shaft diameter.

LRFD 10.8.3.3.1

Shaft Resistance using α-method
$q_r = \phi q_s$, tsf
$Q_r = \phi q_s \pi D(L – 5' – D)$, tons

Where:
$\phi = 0.55$
$q_s = \alpha S_u$, tsf
α = adhesion factor
For $S_u/p_a \leq 1.5$
$\alpha = 0.55$
Otherwise,
$\alpha = 0.55 – 0.1(S_u/p_a – 1.5)$
S_u = mean undrained shear strength, tsf
p_a = atmospheric pressure = 1.06 tsf
L = length of shaft in soil, ft
D = diameter of shaft, ft

LRFD 10.8.3.3.2

Tip Resistance
$q_r = \phi q_p$, tsf
$Q_r = \phi q_p \pi D^2/4$, tons

Where:
$\phi = 0.50$
$q_p = N_c S_u \leq 40.0$ tsf
$N_c = 6[1+0.2*(Z/D)] \leq 9$
Z = penetration of shaft, ft

S_u is determined from undisturbed samples obtained within a depth of 2 diameters below the tip of the shaft.
For $S_u < 0.25$ tsf, N_c shall be reduced by 1/3.
For $S_u > 1.0$ tsf, D > 75.0 in, and when shaft settlements will not be evaluated, q_p shall be reduced to q_{pr}.

Where:
$q_{pr} = q_p F_r$

$$F_r = \frac{2.5}{12.0aD_p + 2.5b} \leq 1.0$$

$a = 0.0071 + 0.0021(Z/D_p) \leq 0.015$

$0.5 \leq b = 0.45\sqrt{2.0S_u} \leq 1.5$

2.2 Cohesionless Soils

LRFD 10.8.3.4

Resistance in Cohesionless Soils

Side Resistance

$Q_r = \phi q_s \pi DL$, tons

Where:

ϕ = 0.55
D = diameter of drilled shaft, ft
L = length of drilled shaft contributing to side resistance, ft
q_s = nominal side resistance of soil, tsf
$q_s = \beta\sigma'_v \le 2.0$ tsf For $0.25 \le \beta \le 1.2$

Where:

$\beta = 1.5 - 0.135\sqrt{z}$ For $N_{60} \ge 15$
$\beta = N_{60}/15*(1.5 - 0.135\sqrt{z})$ For $N_{60} < 15$

If permanent casing is used, the side resistance shall be adjusted with consideration of type and length of casing used.

Tip Resistance

$Q_r = \phi q_p \pi D^2/4$, tons
Where:
ϕ = 0.50
q_p = nominal tip resistance of soil
$q_p = 0.6N_{60} \le 30$ tsf for $N_{60} \le 50$

Tip Resistance Reduction

For drilled shaft diameters > 4.17 ft, q_p should be reduced.
$q_{pr} = 4.17q_p/D_p$

2.3 Rock

LRFD 10.8.3.5

Resistance in Rock

Side resistance from overlying soils may be neglected if drilled shafts are socketed into rock. Where there is permanent casing extending into the rock socket, the length of socket where casing protrudes shall be ignored when calculating the capacity in side resistance.

Side Resistance

$q_s = 0.65\alpha_E p_a(q_u/p_a)^{0.5} < 0.65p_a(f'_c/p_a)^{0.5}$, tsf

$Q_r = \phi q_s(H_s \pi D_s)$, tons

Where:

q_s = side resistance, tsf

q_u = uniaxial compressive strength of the rock, tsf

α_E = determined from LRFD Table 10.8.3.3.4b-1

p_a = atmospheric pressure = 1.06 tsf

f'_c = concrete strength of drilled shaft, tsf

H_s = height of rock socket, ft

D_s = diameter of rock socket, ft

ϕ = 0.55

Tip Resistance

If the rock $1.0D_s$ below the base of the drilled shaft is intact or tightly jointed and the depth of the socket is $> 1.5D_s$, then:

$q_p = 2.5q_u$, tsf

Otherwise,

$q_p = [s^{0.5} + (m*s^{0.5} + s)^{0.5}]q_u$, tsf

$Q_r = \phi q_p(\pi D_s^2/4)$, tons

Where:

ϕ = 0.55

q_p = tip resistance, tsf

m, s = fractured rock properties determined from LRFD Table 10.4.6.3-4

3.81.3 Structural Resistance

1.1 Reinforcement Design

Drilled shaft structural resistance shall be designed similarly to reinforced concrete columns. Strength Limit State load combinations shall be used in the reinforcement design.

LRFD 10.8.5.2

Reinforcing steel shall extend 10 ft. below the point of fixity of the drilled shaft.

If permanent casing is used, and the shell consists of smooth pipe greater than 0.12 in. thick, if may be considered load carrying. An 1/8" shall be subtracted off of the shell thickness to account for corrosion.

Longitudinal Reinforcement

Longitudinal Reinforcement shall be designed to resist bending in the shaft due to lateral loads.

The limits for the longitudinal reinforcement are as follows:

LRFD 5.7.4.2

$0.135A_g f'_c/f_y \leq A_s \leq 0.08A_g$

Where:

A_g = gross cross-sectional area of drilled shaft

f'_c = concrete compressive strength of drilled shaft

f_y = yield strength of reinforcement

A_s = area of reinforcement in drilled shaft

In most cases, the minimum amount of longitudinal reinforcement will be required.

A suggested range for spacing longitudinal reinforcement is 6" to 9" (center to center) to insure concrete flow around reinforcement cage.

Axial Capacity

The axial capacity of a drilled shaft shall be determined by the following equations:

$P_r = \phi P_n$

Where:

LRFD 5.5.4.2.1

$\phi = 0.75$

Shafts w/ Spiral Reinforcement:

LRFD 5.7.4.4

$P_n = 0.85[0.85f'_c(A_g - A_s)+A_s f_y]$

Shafts w/ Tie Reinforcement:

$P_n = 0.80[0.85f'_c(A_g - A_s)+A_s f_y]$

Shear Capacity

Shear reinforcement will need to be designed if:

$V_u > 0.5\phi V_c$

Where:

LRFD 5.5.4.2

ϕ = resistance factor for shear, 0.9

V_u = factored shear force

LRFD 5.8.3.3

$V_c = 0.0316\beta\sqrt{f'_c}\, b_v d_v$

Where:
β = 2.0
b_v = D, diameter of shaft
d_v = 0.9(D/2 + D_r/π)
D_r = diameter of the circle passing through the centers of the longitudinal reinforcement. See commentary LRFD C5.8.2.9-2.

Minimum Reinforcement
The minimum amount of reinforcement must satisfy the following equation:

LRFD 5.8.2.5

$$A_v \geq 0.0316\sqrt{f'_c}\frac{b_v s}{f_y}$$

Where:
A_v = area of transverse reinforcement within distance, *s*
s = spacing of transverse reinforcement
f_y = yield strength of reinforcement

Maximum Spacing
The maximum spacing of transverse reinforcement shall meet the following criteria:

LRFD 5.8.2.7

If $v_u < 0.125f'_c$:
$s_{max} = 0.8d_v \leq 24.0$ in.

If $v_u \geq 0.125f'_c$:
$s_{max} = 0.4d_v \leq 12.0$ in.

Where:
v_u = factored shear stress

Shear Resistance
When shear reinforcement design is required, the following equation applies:

LRFD 5.8.3.3

$V_r = \phi(V_c + V_s)$
Where:
ϕ = 0.9

$$V_s = \frac{A_v f_y d_v \cot\theta}{s}$$

θ = angle of inclination of diagonal compressive stresses = 45°